

# The design of optical triode

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Under the action of pump light, the conventional photonic crystal can be turned into function photonic crystal. In the paper, we have designed optical triode with one-dimensional function photonic crystal, and analyzed the effect of period number, medium thickness and refractive index, incident angle, the irradiation way and intensity of pump light on the optical triode magnification. We obtain some valuable results, which shall help to optimal design optical triode.

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Keywords: One-dimensional photonic crystal; magnification; optical triode

## 1. Introduction

In 1987, E. Yablonovitch and S. John had pointed out that the behavior of photons can be changed when propagating in the material with periodical dielectric constant, and termed such material Photonic Crystal [1, 2], which are designed to affect the propagation of light [3, 4]. An important feature of the photonic crystal is that there are allowed and forbidden ranges of frequencies at which light propagates in the direction of index periodicity. Due to the forbidden frequency range, known as photonic band gap (PBG) [5, 6]. The existence of PBGs will lead to many interesting phenomena, e.g., modification of spontaneous emission [7-10] and photon localization [11-14]. Thus numerous applications of photonic crystal have been proposed in improving the performance of optoelectronic and microwave devices such as high-efficiency semiconductor lasers, light emitting diodes, wave guides, optical filters, high-Q resonators, antennas, frequency-selective surface, optical limiters and amplifiers [15-18]. These applications would be significantly enhanced if the band structure of the photonic crystal could be tuned.

In Refs. [19-25], we have proposed function photonic crystal, which is constituted by two media  $A$  and  $B$ , their refractive indexes are the functions of space position. Unlike conventional photonic crystal (PCs), which is constituted by the constant refractive index media  $A$  and  $B$ . We have studied the transmissivity and the electric field distribution with and without defect layer.

In the paper, we have designed optical triode with one-dimensional function photonic crystal, and analyzed the effect of period number, medium thickness and refractive index, incident angle, the irradiation way and intensity of pump light on the optical triode magnification. We obtain some results: (1) When the period number, medium thickness, incident angle and intensity of pump light increase, the optical triode magnification increases. (2) When the medium refractive index decrease the optical triode magnification increases. (3) The magnification of pump light irradiation way in Fig. 2 is larger than Fig. 3. The above results help to optimal design optical triode.

## 2. The transmissivity of one-dimensional function photonic crystal

In Refs. [19-25], we have given the function photonic crystal transfer matrices  $M_B$  and  $M_A$  of the media  $B$  and  $A$  for the  $TE$  wave, they are

$$M_B = \begin{pmatrix} \cos \delta_b & \frac{-i \sin \delta_b}{\sqrt{\frac{\epsilon_0}{\mu_0}} n_b(b) \cos \theta_i^I} \\ -i n_b(0) \sqrt{\frac{\epsilon_0}{\mu_0}} \cos \theta_t^I \sin \delta_b & \frac{n_b(0) \cos \theta_t^I \cos \delta_b}{n_b(b) \cos \theta_i^I} \end{pmatrix}, \quad (1)$$

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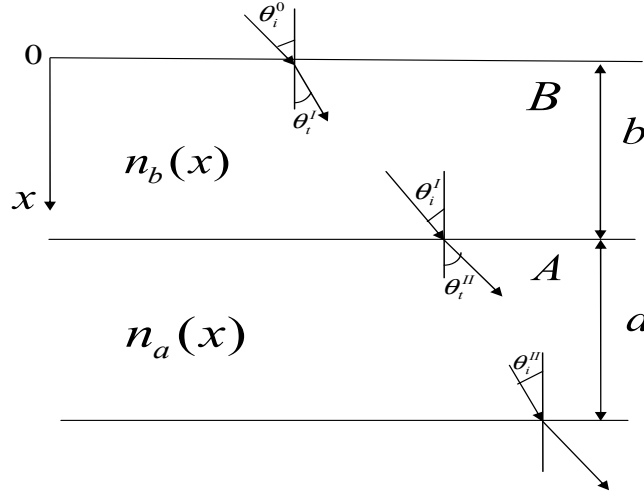


FIG. 1: The light transmission figure in media  $B$  and  $A$  of function photonic crystal.

$$M_A = \begin{pmatrix} \cos \delta_a & -\frac{i \sin \delta_a}{\sqrt{\frac{\varepsilon_0}{\mu_0}} n_a(a) \cos \theta_i^{II}} \\ -in_a(0) \sqrt{\frac{\varepsilon_0}{\mu_0}} \cos \theta_t^{II} \sin \delta_a & \frac{n_a(0) \cos \theta_t^{II} \cos \delta_a}{n_a(a) \cos \theta_i^{II}} \end{pmatrix}, \quad (2)$$

where

$$\delta_b = \frac{\omega}{c} n_b(b) \cos \theta_i^I \cdot b, \quad \delta_a = \frac{\omega}{c} n_a(a) \cos \theta_i^{II} \cdot a, \quad (3)$$

$$\sin \theta_i^I = \frac{n_0}{n_b(b)} \sin \theta_i^0, \quad \cos \theta_i^I = \sqrt{1 - \frac{n_0^2}{n_b^2(b)} \sin^2 \theta_i^0}, \quad \cos \theta_t^I = \sqrt{1 - \frac{n_0^2}{n_b^2(0)} \sin^2 \theta_i^0}, \quad (4)$$

and

$$\sin \theta_i^{II} = \frac{n_0}{n_a(a)} \sin \theta_i^0, \quad \cos \theta_i^{II} = \sqrt{1 - \frac{n_0^2}{n_a^2(a)} \sin^2 \theta_i^0}, \quad \cos \theta_t^{II} = \sqrt{1 - \frac{n_0^2}{n_a^2(0)} \sin^2 \theta_i^0}. \quad (5)$$

In one period, the transfer matrix  $M$  is

$$\begin{aligned} M &= M_B \cdot M_A \\ &= \begin{pmatrix} \cos \delta_b & \frac{-i \sin \delta_b}{\sqrt{\frac{\varepsilon_0}{\mu_0}} n_b(b) \cos \theta_i^I} \\ -in_b(0) \sqrt{\frac{\varepsilon_0}{\mu_0}} \cos \theta_t^I \sin \delta_b & \frac{n_b(0) \cos \theta_t^I \cos \delta_b}{n_b(b) \cos \theta_i^I} \end{pmatrix} \\ &\quad \begin{pmatrix} \cos \delta_a & \frac{-i \sin \delta_a}{\sqrt{\frac{\varepsilon_0}{\mu_0}} n_a(a) \cos \theta_i^{II}} \\ -in_a(0) \sqrt{\frac{\varepsilon_0}{\mu_0}} \cos \theta_t^{II} \sin \delta_a & \frac{n_a(0) \cos \theta_t^{II} \cos \delta_a}{n_a(a) \cos \theta_i^{II}} \end{pmatrix}. \end{aligned} \quad (6)$$

Where  $n_b(0)$ ,  $n_b(b)$ ,  $n_a(0)$  and  $n_a(a)$  are the starting point and endpoint values of refractive indices for media  $B$  and  $A$ ,  $b$  and  $a$  are the thickness of media  $B$  and  $A$ ,  $\theta_i^0$  is incident angle,  $n_0$  is air refractive index, and the angles  $\theta_t^I$ ,  $\theta_i^I$ ,  $\theta_t^{II}$  and  $\theta_i^{II}$  are shown in FIG. 1.

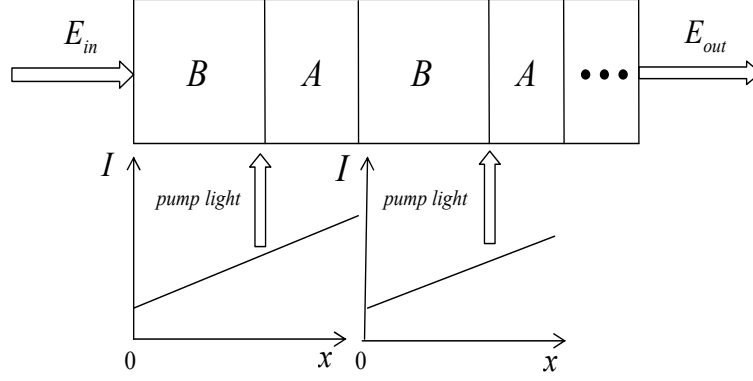


FIG. 2: The pump light irradiate vertically photonic crystal, its one-period irradiate medium ( $BA$ ).

We can find the transfer matrix  $M$  of the function photonic crystal is more complex than the conventional PCs. For the structure  $(BA)^N$  function photonic crystal, its characteristic equation is

$$\begin{aligned} \begin{pmatrix} E_1 \\ H_1 \end{pmatrix} &= M_B M_A M_B M_A \cdots M_B M_A \begin{pmatrix} E_{N+1} \\ H_{N+1} \end{pmatrix} \\ &= M \begin{pmatrix} E_{N+1} \\ H_{N+1} \end{pmatrix} = \begin{pmatrix} A & B \\ C & D \end{pmatrix} \begin{pmatrix} E_{N+1} \\ H_{N+1} \end{pmatrix}. \end{aligned} \quad (7)$$

With the total transfer matrix  $M$ , we can obtain the transmission coefficient  $t$ , it is

$$t = \frac{E_{N+1}}{E_{in}} = \frac{E_{out}}{E_{in}} = \frac{2\eta_0}{A\eta_0 + B\eta_0\eta_{N+1} + C + D\eta_{N+1}}, \quad (8)$$

where  $E_1 = E_{in} + E_r$ ,  $E_{in}$  is the incident electric field,  $E_r$  is the reflected electric field,  $E_{N+1} = E_{out}$  is the output electric field and  $\eta_0 = \eta_{N+1} = \sqrt{\frac{\epsilon_0}{\mu_0}} \cos \theta_i^0$ .

## 2. The design principle of optical triode

In Refs. [20-25], we can find the transmissivity can be larger than 1 and the output electric field intensity has been magnified for the function photonic crystal that the refractive indexes of media  $B$  and  $A$  are the increasing functions with the space position. In Refs. 23 and 25, we have designed and optimally designed optical device, such as optical amplifier, attenuator, and optical diode by the function photonic crystal.

In the following, we shall explain how to turn the conventional photonic crystal into the function photonic crystal, and give the design principle of optical triode. In nonlinear optics, the medium refractive index is the linear function of light intensity  $I$ , which is called the optical kerr effect, it is

$$n(I) = n_0 + n_2 I, \quad (9)$$

where  $n_0$  represents the usual, weak-field refractive index, the optical Kerr coefficient  $n_2 = \frac{3}{4n_0^2\epsilon_0 c} \chi^{(3)}$ , and  $\chi^{(3)}$  is the third-order nonlinear optical susceptibility.

In Fig. 2, in the perpendicular to the direction of incident light, we join the strong laser field (pump light) to every one-period  $BA$  of conventional photonic crystal respectively, the intensity  $I$  distribution is the function of space position. Here, the pump light intensity  $I$  is the linear function of every one-period  $BA$  thickness  $x$  and width  $y$ , it is

$$I = I_0(x \times y), \quad (10)$$

the intensity distribution  $I$  is evenly in the  $y$  direction, we can let  $y = 1$ .

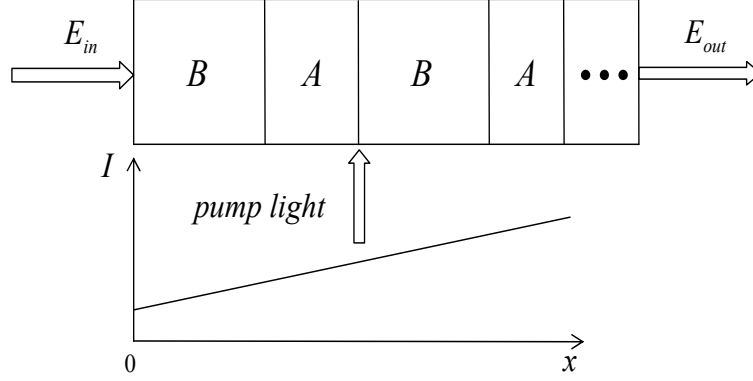


FIG. 3: The pump light irradiate vertically photonic crystal, its one-period irradiate medium  $(BA)^2$ .

Substituting Eq. (10) into (9), there is

$$n(x) = n_0 + n_2 I_0 x, \quad (11)$$

where  $I_0$  is the intensity coefficient of pump light, the optical kerr effect of incident light is neglected. The conventional medium refractive index  $n_0$  become the linear function  $n(x)$  of space position  $x$ , i.e., the refractive indices  $n_b$  and  $n_a$  of conventional media  $B$  and  $A$  become the linear functions  $n_b(x)$  and  $n_a(x)$ . The Fig. 2 has turned the conventional photonic crystal into the function photonic crystal with the pump light. At every one-period  $BA$ , the refractive indexes starting point and endpoint value of media  $B$  and  $A$  are same, they are

$$n_b(0) = n_b, \quad n_b(b) = n_b + n_2 I_0 b, \quad (12)$$

$$n_a(0) = n_a + n_2 I_0 b, \quad n_a(a) = n_a + n_2 I_0 (a + b), \quad (13)$$

where  $n_b(n_a)$  is the refractive index of conventional medium  $B(A)$  (without joining pump light),  $n_b(0)(n_a(0))$ ,  $n_b(b)(n_a(a))$  are the refractive indices starting point and endpoint value of function medium  $B(A)$  (with joining pump light), and  $b(a)$  is the thickness of media  $B(A)$ . In every one-period, the refractive indices of media  $B$  and  $A$  are the linear functions of space position  $x$ .

In Fig. 3, we join the pump light to photonic crystal every two-period  $(BA)^2$ , respectively. The pump light intensity  $I$  is the linear function of every two-period  $(BA)^2$  thickness  $x$ . At every two-period, the refractive indexes of media  $B$  and  $A$  are same, they are

$$n_{1b}(0) = n_b, \quad n_{1b}(b) = n_b + n_2 I_0 b, \quad (14)$$

$$n_{1a}(0) = n_a + n_2 I_0 b, \quad n_{1a}(a) = n_a + n_2 I_0 (a + b), \quad (15)$$

$$n_{2b}(0) = n_b + n_2 I_0 (b + a), \quad n_{2b}(b) = n_b + n_2 I_0 (2b + a), \quad (16)$$

$$n_{2a}(0) = n_a + n_2 I_0 (2b + a), \quad n_{2a}(a) = n_a + n_2 I_0 (2b + 2a), \quad (17)$$

where  $n_{1b}(0)(n_{1a}(0))$ ,  $n_{1b}(b)(n_{1a}(a))$  are the refractive index starting point and endpoint value of the first period medium  $B(A)$ , and  $n_{2b}(0)(n_{2a}(0))$ ,  $n_{2b}(b)(n_{2a}(a))$  are the refractive index starting point and endpoint value of the second period medium  $B(A)$ . In every two-period, the refractive indices of media  $B$  and  $A$  are linear functions of space position  $x$ .

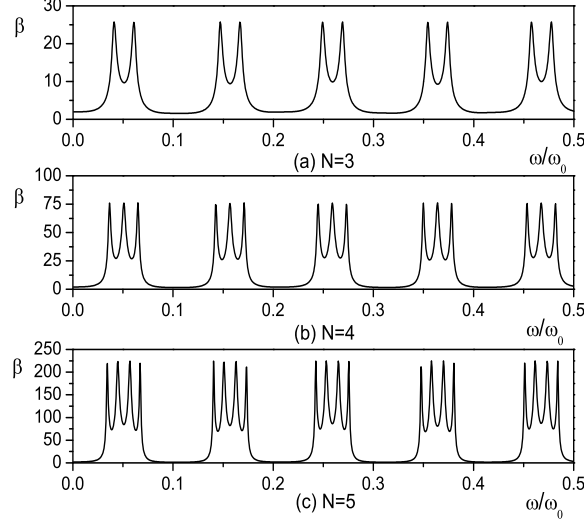


FIG. 4: The effect of period numbers  $N$  on magnification  $\beta$  under the pump light action of Fig. 2. (a)  $N = 3$ , (b)  $N = 4$  and (c)  $N = 5$ .

The function photonic crystal Figs. 2 and 3 should be designed optical triode, the optical triode magnification  $\beta$  is defined as

$$\beta = |t| = \left| \frac{E_{out}}{E_{in}} \right| = \left| \frac{2\eta_0}{A\eta_0 + B\eta_0\eta_{N+1} + C + D\eta_{N+1}} \right|. \quad (18)$$

### 3. Numerical result

In this section, we report our numerical results of the optical triode magnification  $\beta$  for the one-dimensional function photonic crystal. The main parameters are: The media  $B$  and  $A$  thickness  $b = 398nm$ ,  $a = 208nm$ , and the conventional media  $B$  and  $A$  (without joining pump light) refractive indices  $n_b = 1.68$ ,  $n_a = 2.56$ , the incident angle  $\theta_i^0 = 0$ , the central frequency  $\omega_0 = 1.216 \times 10^{15}Hz$ , the optical Kerr coefficient  $n_2$  in the range of  $9.0 \times 10^{-17} \sim 2.3 \times 10^{-6}(cm^2/W)$ , we take  $n_2 = 10^{-6}(cm^2/W)$  and the light intensity coefficient  $I_0 = 2.2 \times 10^9(cm^2/W)$ . Firstly, we calculate the optical triode magnification  $\beta$  under the pump light action of Fig. 2. Substituting Eqs. (12) and (13) into (6), we can obtain the transfer matrix  $M$  of one period, with Eqs. (7), (8) and (18), we can calculate the magnification  $\beta$ , they are shown in Figs. 4-9, which give the relation between magnification  $\beta$  and incident light frequency  $\omega$ . In Fig. 4 (a), (b) and (c), we give the magnification  $\beta$  corresponding to period numbers  $N = 3$ ,  $N = 4$  and  $N = 5$ , respectively. From Fig. 4, we can obtain some results: (1) The magnification  $\beta$  is related to the incident light frequency, the incident electric field of certain frequencies get through the function photonic crystal, the output electric field have been magnified obviously. (2) When period numbers  $N = 3$ ,  $N = 4$  and  $N = 5$ , the magnifications amplitude  $\beta_{max}$  are 25, 75 and 225, i.e., the output electric field intensity is  $\beta_{max}$  multiple of input electric field intensity, which is shown in Fig. 5. The Fig. 5 (a) and (b) are input electric field and output electric field, respectively. The output electric field has been magnified. In Fig. 6 (a) and (b), the media  $B$  thicknesses are  $b = 398nm$  and  $498nm$ , we can find the magnification  $\beta$  increases with media  $B$  thickness increasing. In Fig. 7 (a) and (b), the media  $B$  refractive indices are  $n_b = 1.68$  and  $n_b = 1.98$ , we can find the magnification  $\beta$  decreases with media  $B$  refractive index increasing. In Fig. 8 (a) and (b), the intensity coefficients  $I_0$  of pump light are  $I_0 = 2.2 \times 10^9(cm^2/W)$  and  $I_0 = 3.2 \times 10^9(cm^2/W)$ , we can find the magnifications amplitude  $\beta_{max}$  increases with the intensity coefficients increasing. In Fig. 9 (a), (b) and (c), we give the magnification  $\beta$

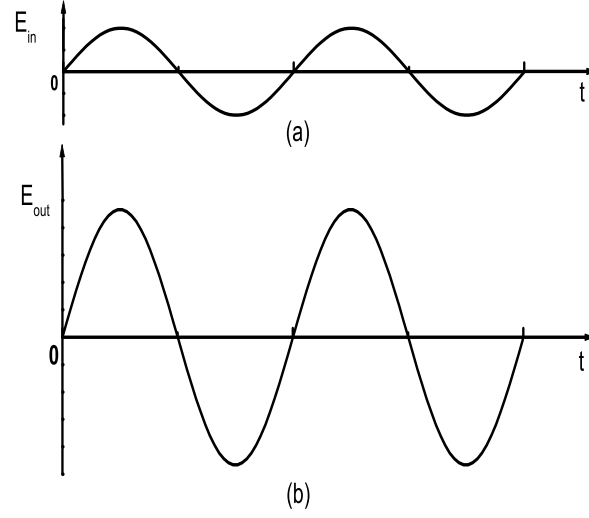


FIG. 5: The input and output electric field of photonic crystal. (a) The input electric field  $E_{in}$ . (b) The output electric field  $E_{out}$  has been amplified, and there are  $E_{out} = \beta E_{in}$ .

corresponding to incident angles  $\theta_i^0 = \frac{\pi}{12}$ ,  $\theta_i^0 = \frac{\pi}{6}$  and  $\theta_i^0 = \frac{\pi}{3}$ , respectively. From Fig. 9, we can obtain some results: (1) The magnifications amplitude  $\beta_{max}$  increases with incident angle increasing. (2) When incident angle  $\theta_i^0 = \frac{\pi}{12}$ ,  $\theta_i^0 = \frac{\pi}{6}$  and  $\theta_i^0 = \frac{\pi}{3}$ , the  $\beta_{max}$  are 80, 90 and 120. Nextly, we calculate the optical triode magnification  $\beta$  under the pump light action of Fig. 3. Substituting Eqs. (14) to (17) into (1) and (2), we can obtain the transfer matrices  $M_{B1}$ ,  $M_{A1}$ ,  $M_{B2}$  and  $M_{A2}$ , and the transfer matrix of one period is  $M = M_{B1}M_{A1}M_{B2}M_{A2}$ . With Eqs. (7), (8) and (18), we can calculate the magnification  $\beta$ , which is shown in Fig. 10. In Fig. 10 (a), (b) and (c), we give the magnification  $\beta$  corresponding to period numbers  $N = 4$ ,  $N = 6$  and  $N = 8$ , respectively. From Fig. 10, we can obtain some results: (1) The magnifications amplitude  $\beta_{max}$  increases with period numbers increasing, when period numbers  $N = 4$ ,  $N = 6$  and  $N = 8$ , the  $\beta_{max}$  are 15, 70 and 250. (2) For the different irradiation way of pump light (Figs. 2 and 3), the  $\beta - \omega$  distribution and the magnifications amplitude  $\beta_{max}$  are different. Obviously, the irradiation way of Fig. 2 can obtain the more magnification.

The reason of optical triode realizing the light amplification is the incident light absorb the pump light energy. We can compare the triode triode with electronic triode. The incident and output electronic fields are the equal of the input and output alternating electrical signals, and the pump light amount to direct-current power.

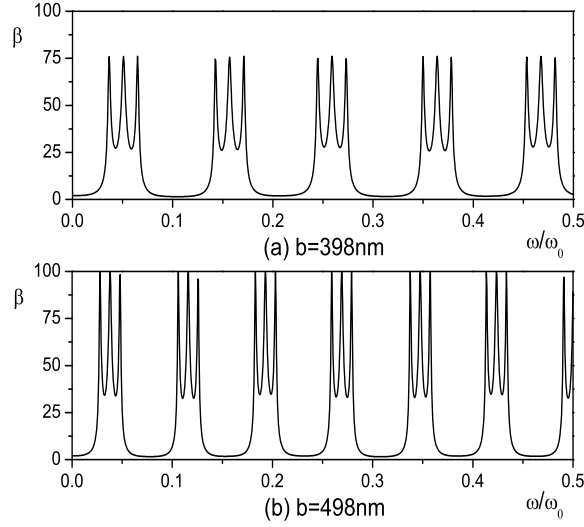


FIG. 6: The effect of medium  $B$  thickness on magnification  $\beta$  under the pump light action of Fig. 2. (a)  $b = 398nm$  and (b)  $b = 498nm$ .

#### 4. Conclusion

In summary, we have designed optical triode with one-dimensional function photonic crystal. We analyzed the effect of period number, medium thickness and refractive index, incident angle, the irradiation way and intensity of pump light on the optical triode magnification  $\beta$ , and obtained some results: (1) When the period number, medium thickness, incident angle and intensity of pump light increase, the optical triode magnification increases. (2) When the medium refractive index decrease the optical triode magnification increases. (3) The magnification of pump light irradiation way in Fig. 2 is larger than Fig. 3. The above results help to optimal design optical triode.

#### 5. Acknowledgment

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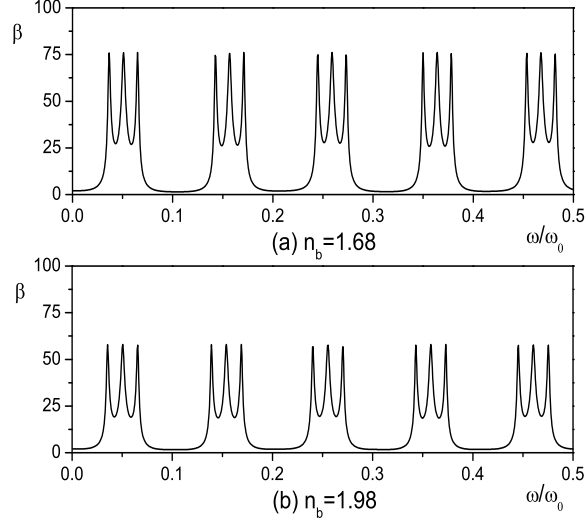


FIG. 7: The effect of medium  $B$  refractive index on magnification  $\beta$  under the pump light action of Fig. 2. (a)  $n_b = 1.68$  and (b)  $n_b = 1.98$ .

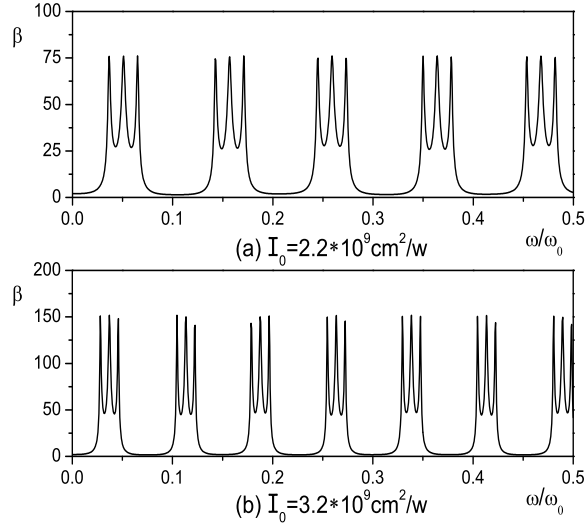


FIG. 8: The effect of the intensity coefficient  $I_0$  on magnification  $\beta$  under the pump light action of Fig. 2. (a)  $I_0 = 2.2 \times 10^9 (\text{cm}^2/\text{W})$  and (b)  $I_0 = 3.2 \times 10^9 (\text{cm}^2/\text{W})$ .

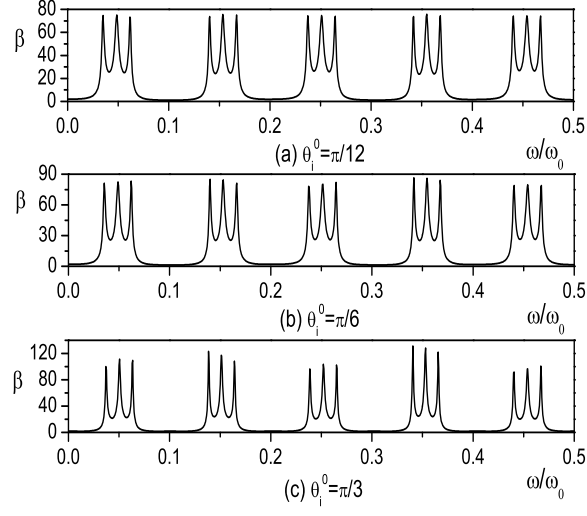


FIG. 9: The effect of the incident angle  $\theta_i^0$  on magnification  $\beta$  under the pump light action of Fig. 2. (a)  $\theta_i^0 = \frac{\pi}{12}$ , (b)  $\theta_i^0 = \frac{\pi}{6}$  and (c)  $\theta_i^0 = \frac{\pi}{3}$ .

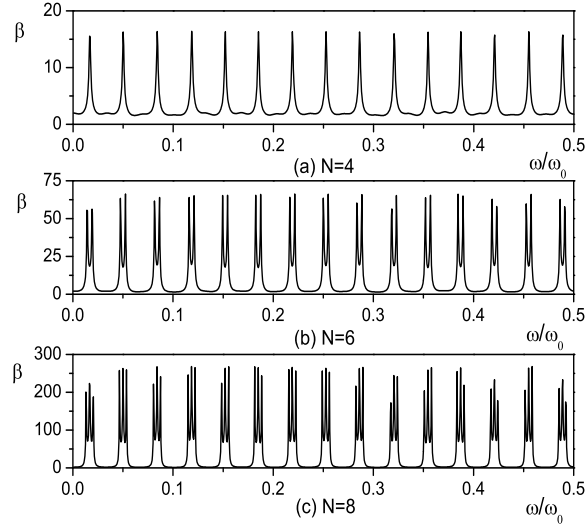


FIG. 10: The effect of period numbers  $N$  on magnification  $\beta$  under the pump light action of Fig. 3. (a)  $N = 4$ , (b)  $N = 6$  and (c)  $N = 8$ .